SunShot
U.S. Department of Energy

Enabling 100s GW of Solar

SunShot Systems Integration R&D Program Overview

energy.gov/sunshot

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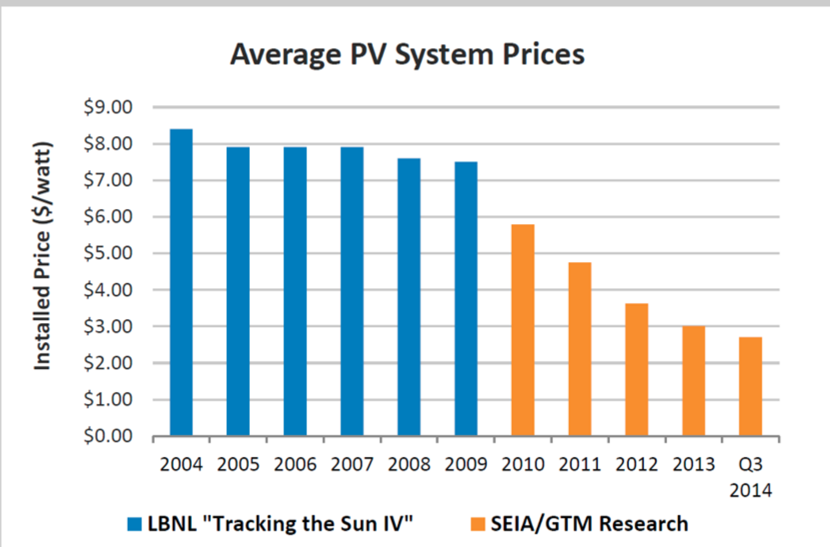
Outlines

- SunShot Vision and Goals
- Challenges and opportunities
- Recent progress in SunShot funded R&D
  - Solar forecasting
  - PV Hosting capacity
  - Smart inverters
  - Interconnection codes and standards
- Future work

Growth of Solar in the U.S.

Installed cost of solar system rapidly decreasing

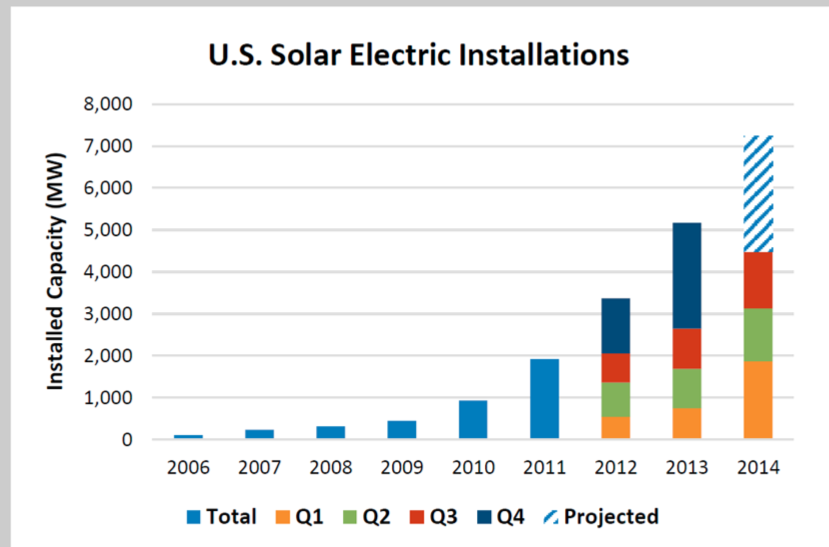
(< $2/W for utility–scale system)



© 2014

Installed solar generation capacity rapid increasing

(>20 GW cumulative by end of 2014)



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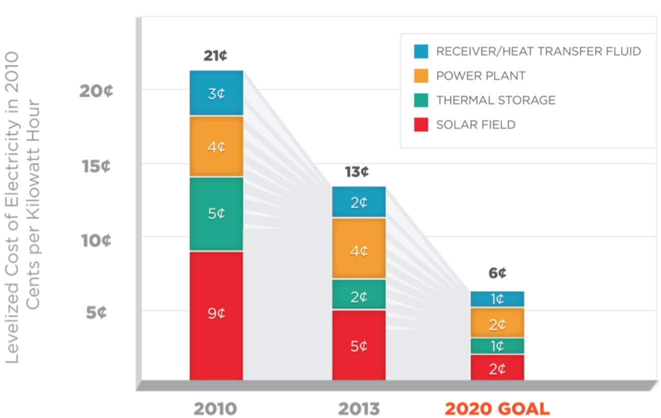
SunShot Cost Reduction Goals

<u>SunShot Goal:</u> Reduce the total installed cost of solar energy systems by 75%, reaching $1/W or $0.06 per kilowatt-hour (kWh) by 2020.

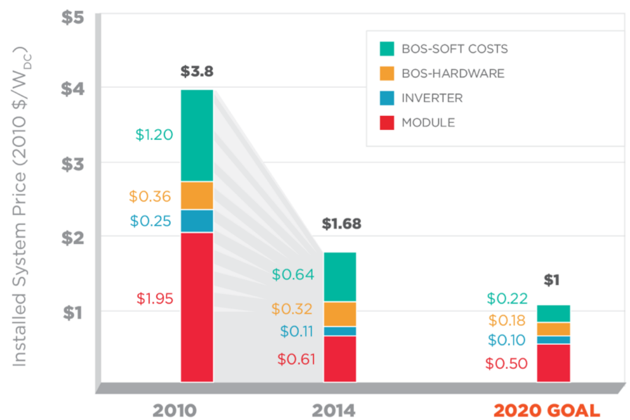
As of 2014, SunShot is 60% of its way toward achieving the cost target.

The Falling Cost of Concentrating Solar Power

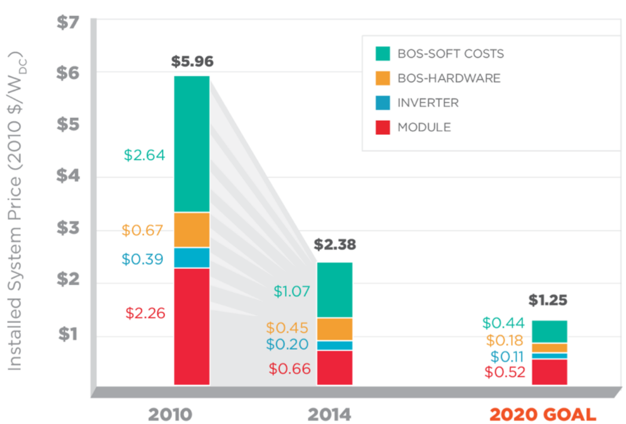
CSP



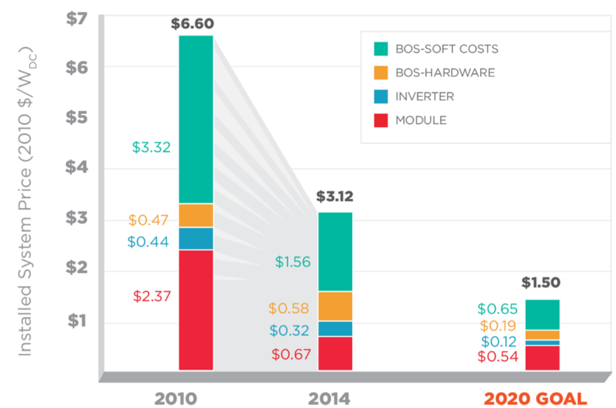
Utility-Scale PV



Commercial PV

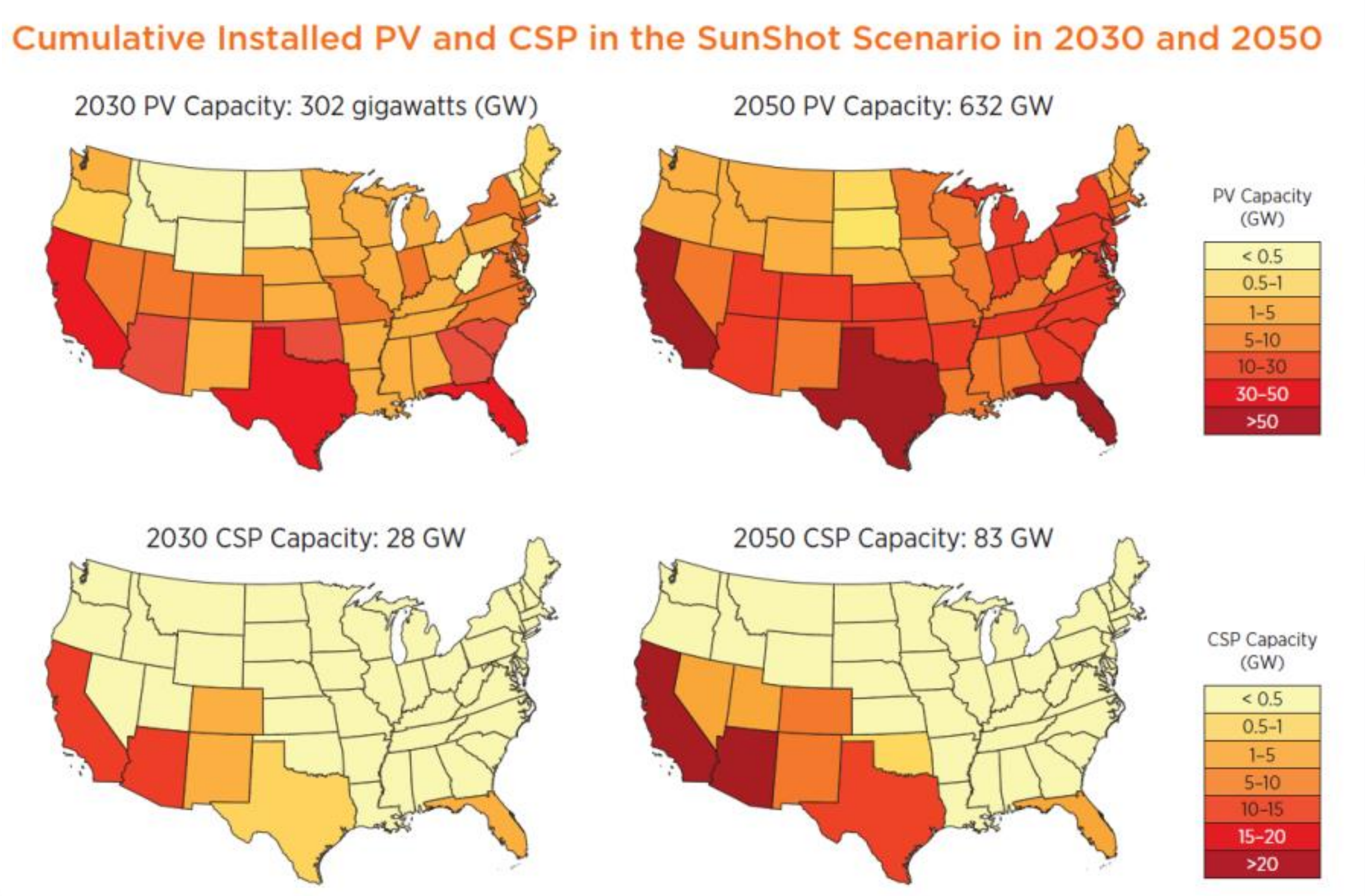


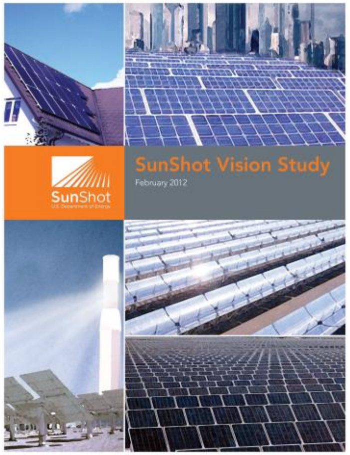
Residential PV



SunShot Vision on Deployment

Solar can meet **14% (300GW)** by 2030 and **27% (600 GW)** by 2050 of U.S. electricity demand





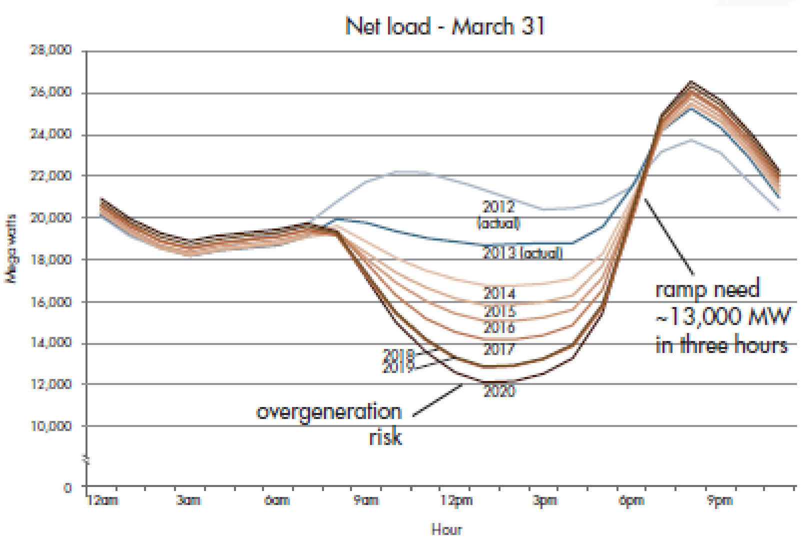
DOE SunShot Vision Study (2012)

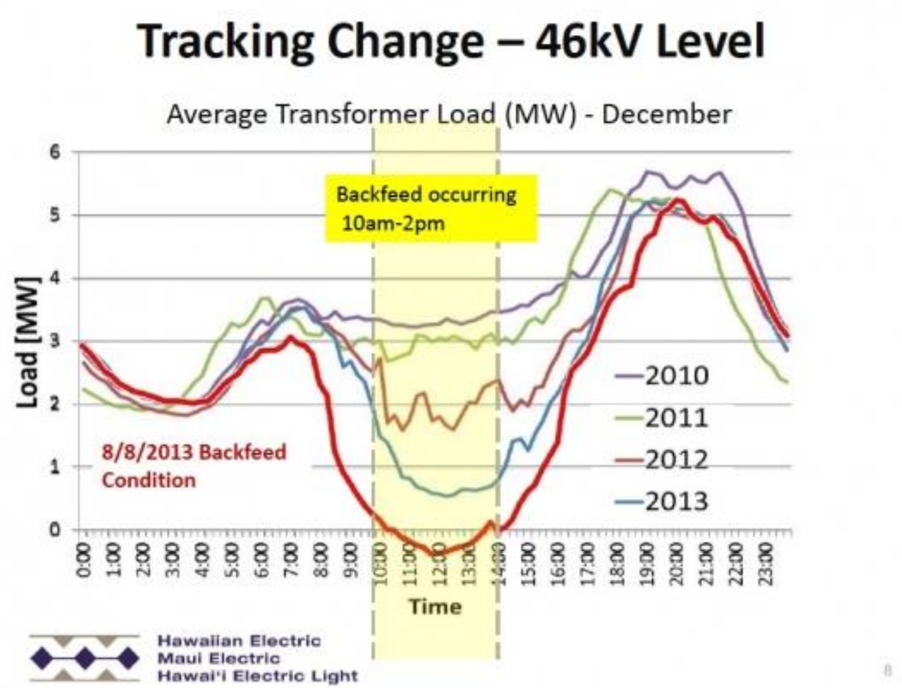
The Hot Spots!

- Germany:
  - 38 GW as of 2014, about 20% by generation capacity, 7% by energy
  - **On June 9th, solar peaked at 24 GW, supplying 50 percent of instantaneous demand.**
  - Grid Code mandating the use of smart inverters.
- California:
  - 33% by 2020 and 50% by 2030 preferred renewable resources
  - **In 2015, Instantaneous solar generation > 6GW, about 10% by capacity, >5% by energy.**
  - CPUC is mandating smart inverters through Rule 21 revision.
- Hawaii:
  - 100% renewable energy by 2045
  - **In 2015, 400 MW installed capacity, 48,000 distributed rooftop solar, 6% by energy**
  - In some areas **>100% day time minimum loads.**
  - Through the inverter testing work at NREL, HECO decided to raise allowable solar penetration threshold from 120 to 250 percent of DML
- Texas:
  - Austin Energy received bids of **4c/KWh for 1.2GW of utility-scale solar, which is below all-in cost of natural gas plants.** It projects the cost of solar energy can be as low as $20/MWh at 2020. (GTM)

Increasing Ramp Rate due to High Penetration of Solar

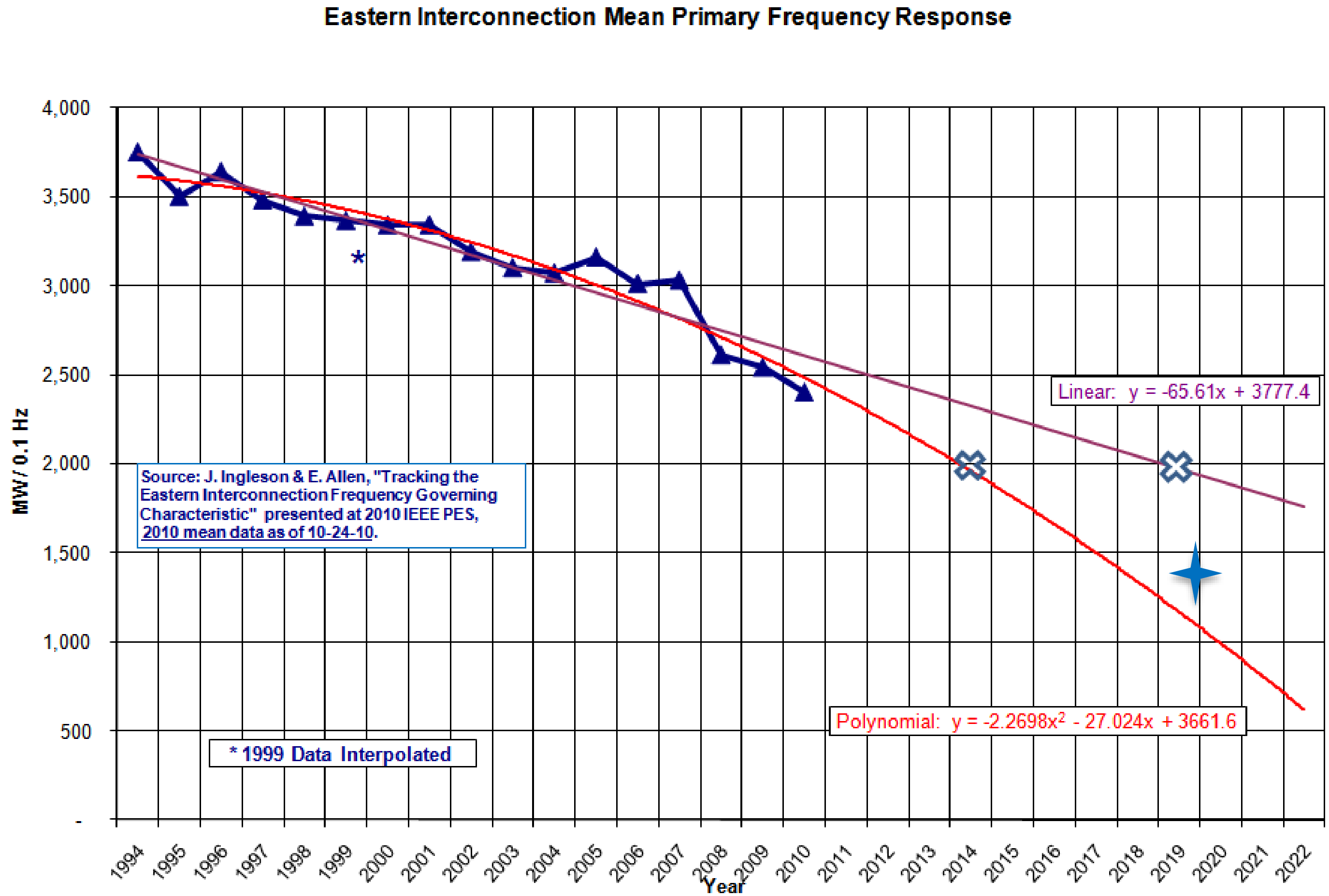
CAISO “Duck Curve”





HECO “Nessie Curve”

Frequency Response Concerns



- Frequency response is decreasing (EI requirement is -1002 MW/0.1 Hz)
- System inertia is decreasing due to inverter-based generation (wind, solar)
- Also, load response to frequency is changing

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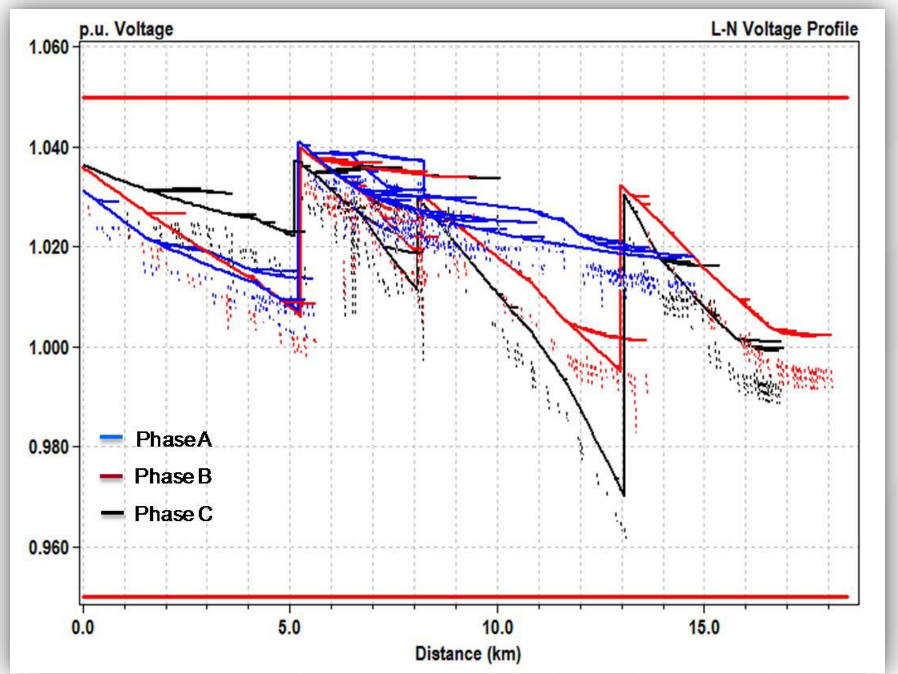
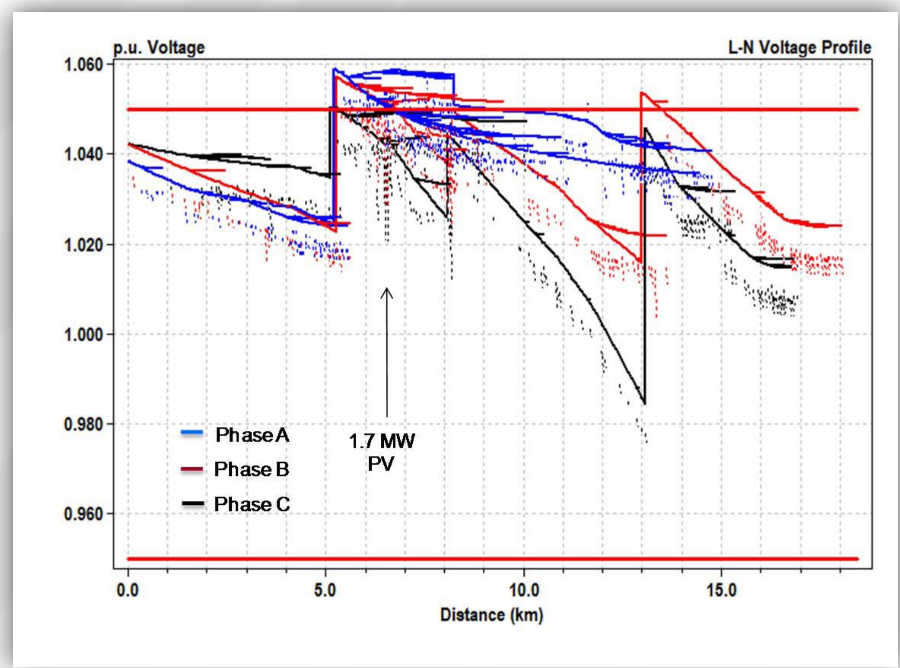
Source: Robert Cummings, NREC

Distribution Voltage Issues

Without PV



With PV



- Reverse power flow
- Solar variability and intermittency
- Voltage fluctuation

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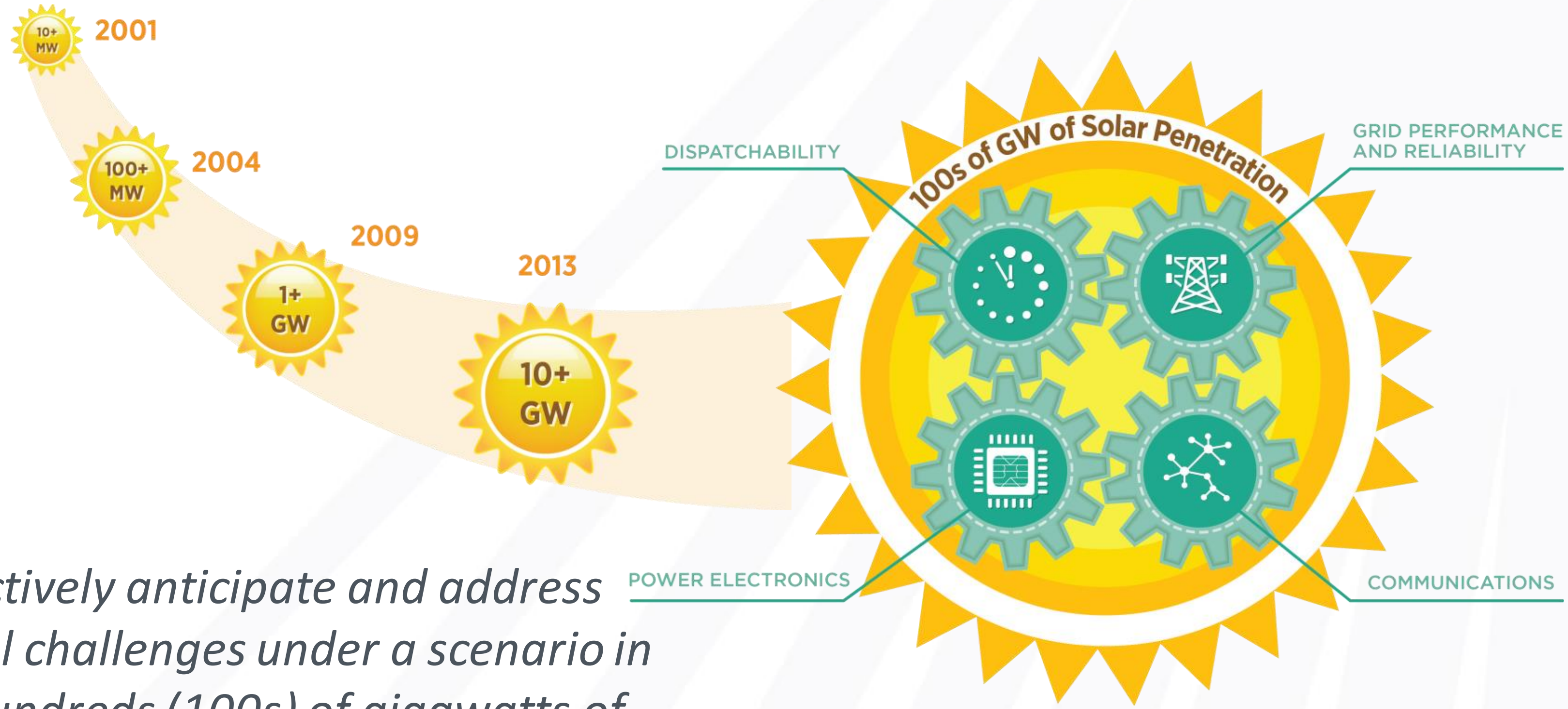
Summary of Technical and Market Challenges

Transmission		Distribution	
Dispachability	• Variable and uncertain resources • Cycling and ramping of conventional generation (Flexibility requirements) • Generation curtailment	Voltage	• Overvoltage • Voltage deviations • Unbalance
Grid Reliability	• Impact on operating reserves • Impact on resource expansion planning • Transmission utilization patterns	Protection	• Increased fault current contribution • Sympathetic tripping + fuse saving • Two-way power flow
Grid Stability	• Large-scale system stability • Frequency response and AGC • Small signal stability and decreasing system inertia	Unintentional Islanding	• Safety and anti-islanding scheme • Transient overvoltage • Out of phase reclosing and decrease reliability
Modeling, Codes and Standards	• Steady-state and transient stability models • Short-circuit and dynamic simulation models • Interconnection and grid performance standards (NERC, IEEE 1547)	Distribution Modeling Tools	• Quasi Static Time Series Analysis ** • Hosting Capacity, Feeder Classification • Feeder monitoring devices, Interoperability
Market Operation	• Rigorous production cost modeling • Ancillary services market • RTO/ISO and BA processes	Visibility and Control	• Traditional Voltage Regulation Equipment • Smart Inverters • Holistic control across the feeder
		Interconnect-ion Process	• Interconnection Standards (IEEE 1547) • Impact studies • Utility Planning and Operation tools

SunShot Systems Integration Vision

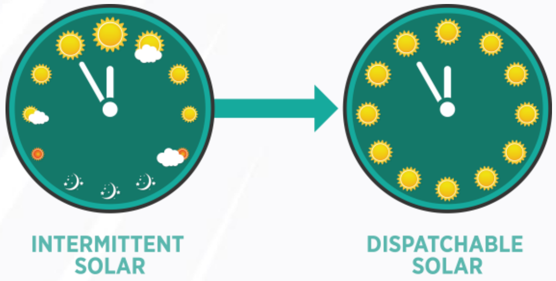


To proactively anticipate and address potential challenges under a scenario in which hundreds (100s) of gigawatts of solar energy are interconnected to the electricity grid, the SI sub-program has identified the challenges to be addressed in four broad, inter-related areas:

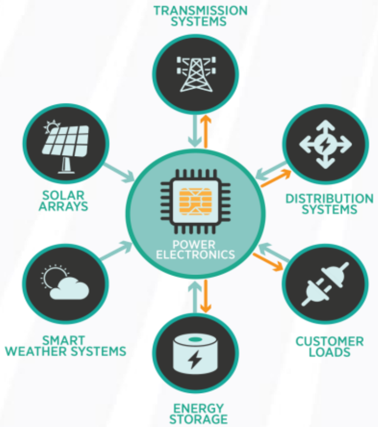
Four Focused Areas

Grid Performance and Reliability: Maintain and enhance the efficiency and reliability of electric transmission and distribution systems in a cost-effective, safe manner with hundreds of gigawatts of solar generation deployed onto the nation's power system.
Dispatchability: Ensure that solar power is available on-demand, when and where it is needed and at the desired amounts, in a manner that is comparable to or better than conventional power plants.
Power Electronics: Develop intelligent devices that maximize the power output from solar power plants and interface with the electric grid (or end use circuits), while ensuring overall system performance, safety, reliability, and controllability at minimum cost.
Communications: Create infrastructure that is used to inform, monitor and control generation, transmission, distribution and consumption of solar energy effectively under broad temporal and spatial scales.

SHINES (2015)



SEGIS-AC (2011)



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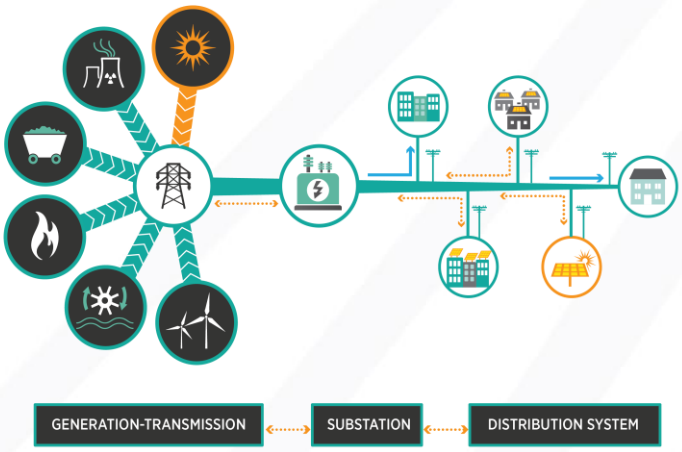
Major Challenges Under High Penetration Scenarios

- Two-way Power Flow
- Dynamic Characteristics of Solar Generation
- Coupled Transmission Grid and Distribution System
- Integration of Sensors, Communications and Data Science Technologies into Power Systems

Grid Performance and Reliability



Communications

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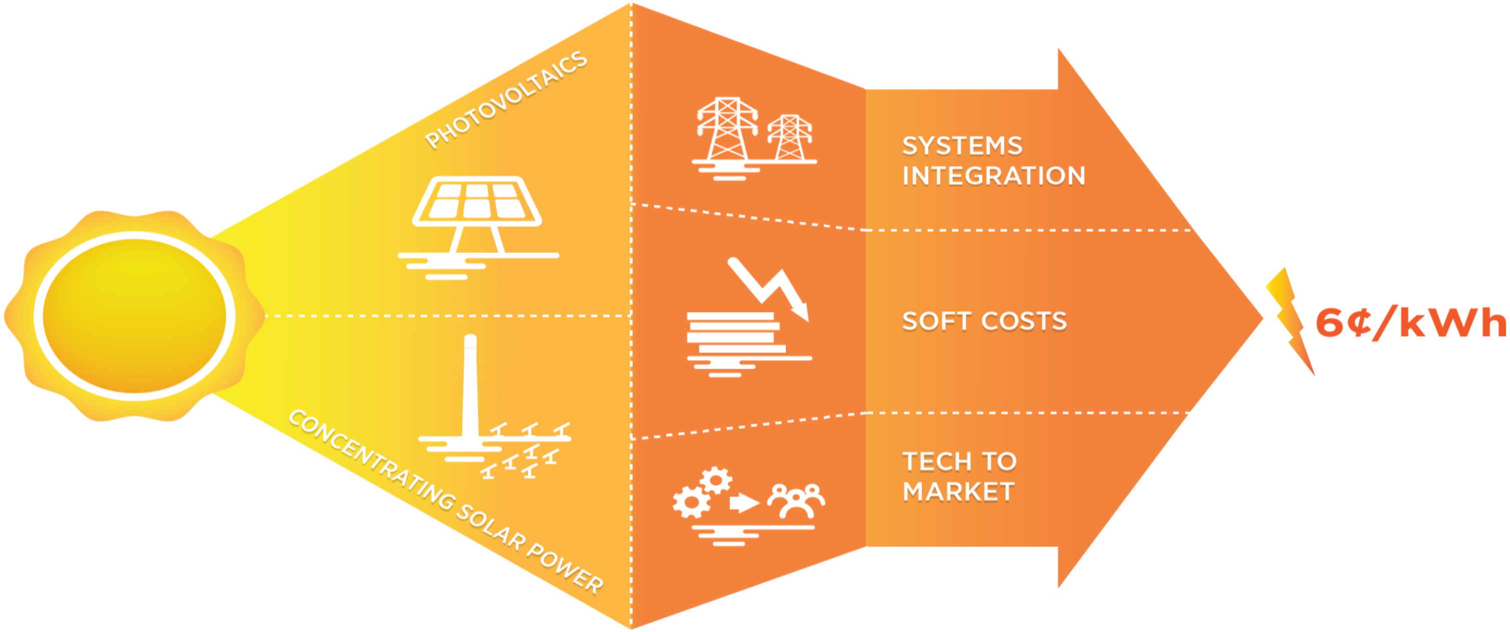
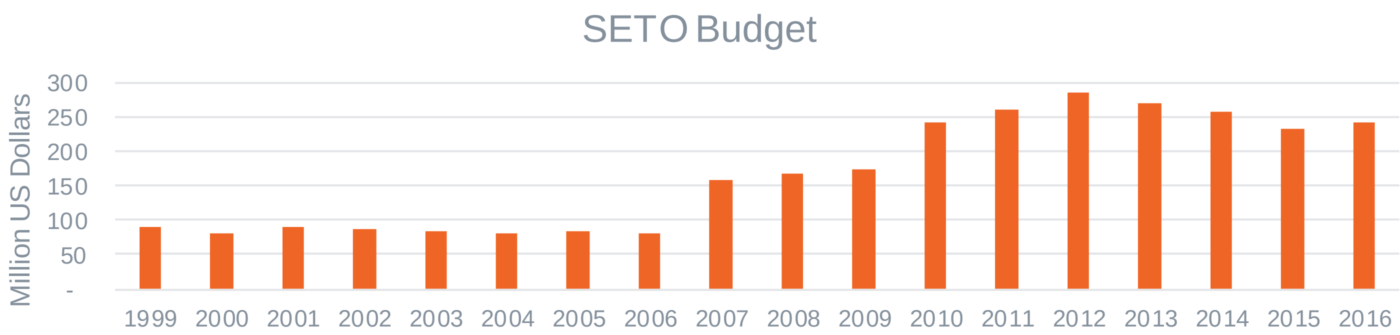
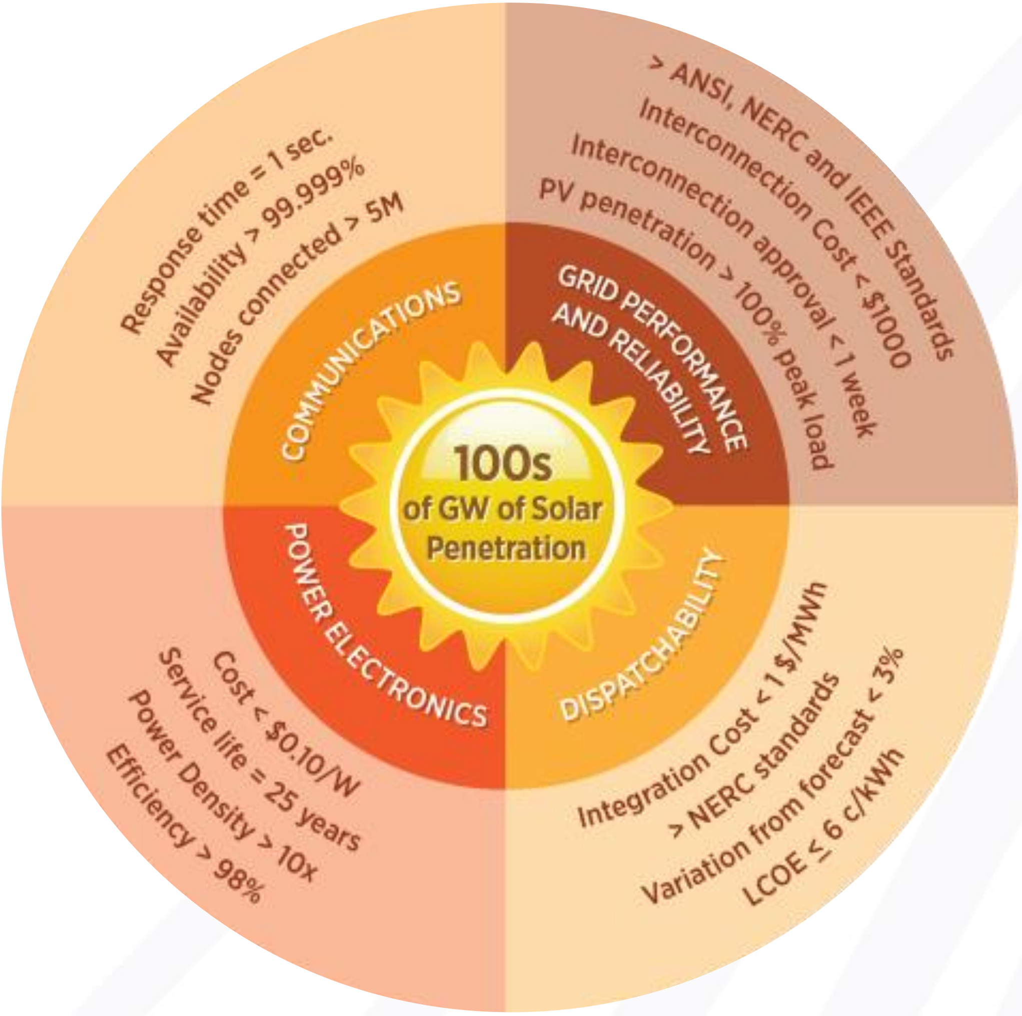
SunShot Initiative





SunShot Systems Integration



SuNLaMP (2015)

SHINES (2015)

SUNRISE (2013)

National Lab R&D (2012)

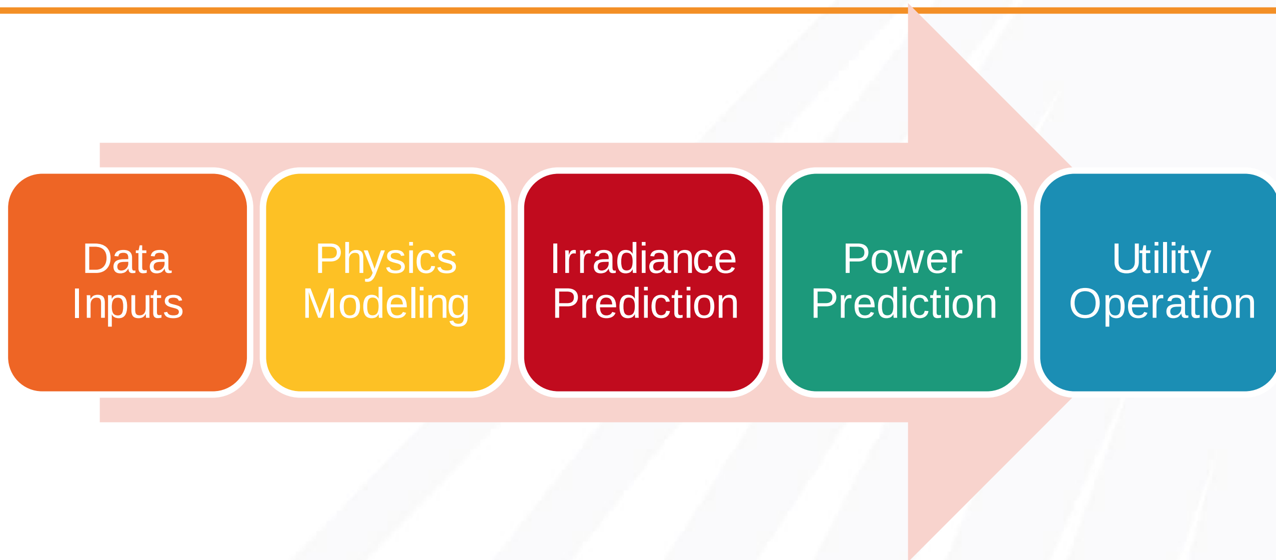
Hi-Pen (2012)

Plug and Play (2012)

Solar Forecasting (2012)

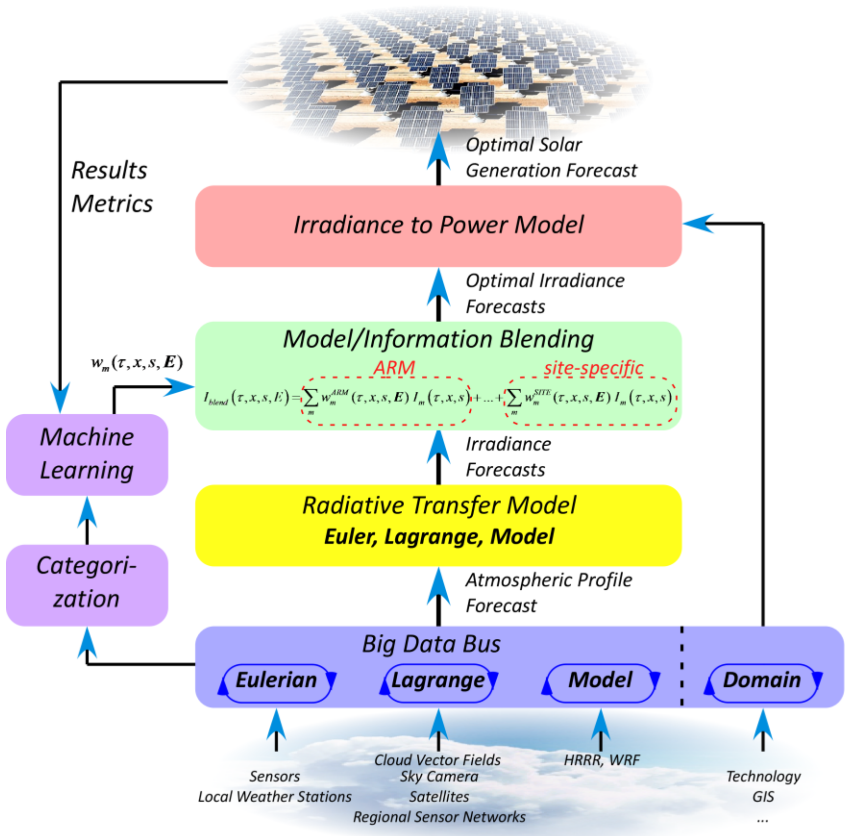
SEGIS-AC (2011)

Solar Forecasting



Forecasting Type	Forecasting Horizon	Existing Methods	Input Data / Sensors
Long-term	24-48 hours (Day Ahead)	NWP models	Satellite, ground and sensors
Mid-term	6-12 hours	Numerical Weather Prediction (NWP)	Satellite, ground and sensors
Short-term	1-6 hours (Hour Ahead)	Satellite images	Satellite
Real-time	1-60 minutes	Persistence algorithms	Total sky imager, radiometers

Solar Forecasting: IBM Machine Learning Approach



Develop a general and scalable technology platform for improved solar forecasting by

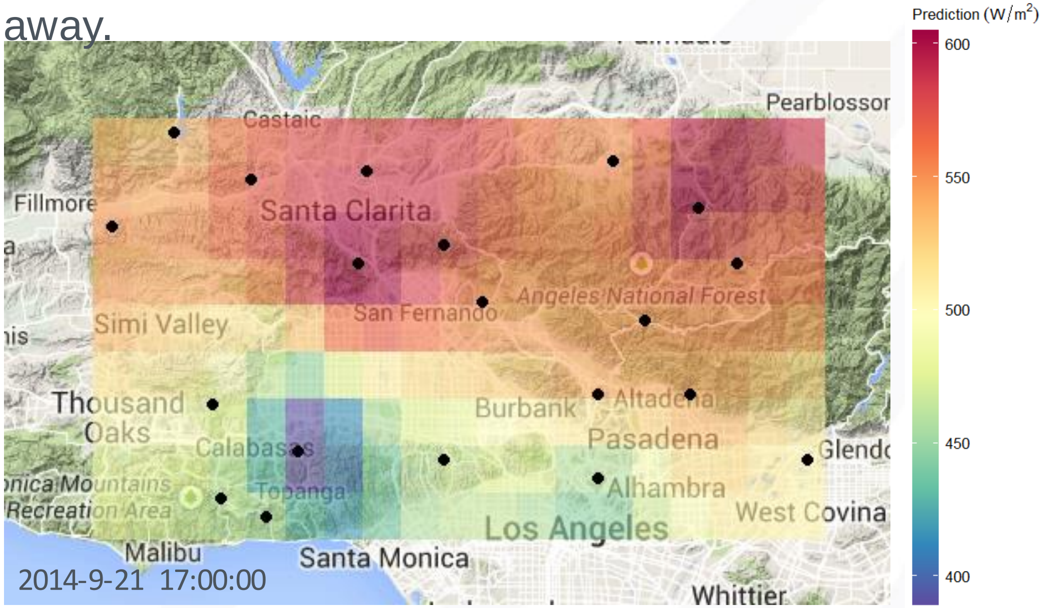
- using big-data information processing technologies;
- applying deep machine learning technologies to blend outputs from multiple models and to enhance intelligence, adaptability and scalability of the technology; and
- leveraging ARM and/or SURFRAD/ISIS data sets to account for cloud opacity, dissipation and formation processes.

- **System provides a *platform* to optimally leverage current and future forecasting capabilities and models.**
- **Machine-learnt blending coefficients will provide guidance to improve weather models**

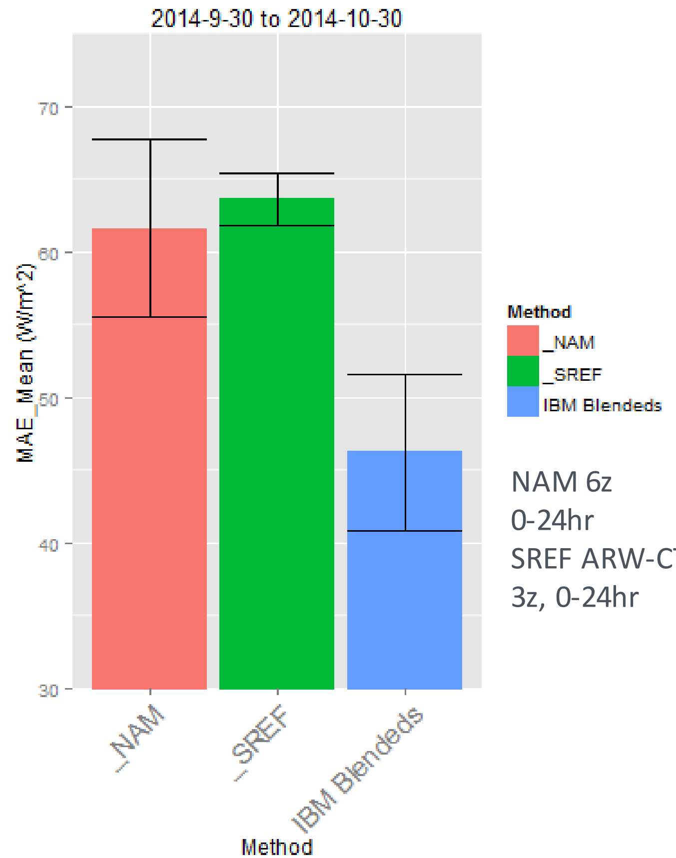
IBM: Gridded Forecast Improved by 25%

- Use the observation network as "anchors" to train model blending for arbitrary location.
- Create gridded forecast independent of measurement

Input model: NOAA NAM 18z run, SREF212 CTL 15z run
Model blending: Trained used "proxy site" 20 to 40 mile away.



Day Ahead Solar Irradiance Forecast
Error Bar: Standard Error of Mean

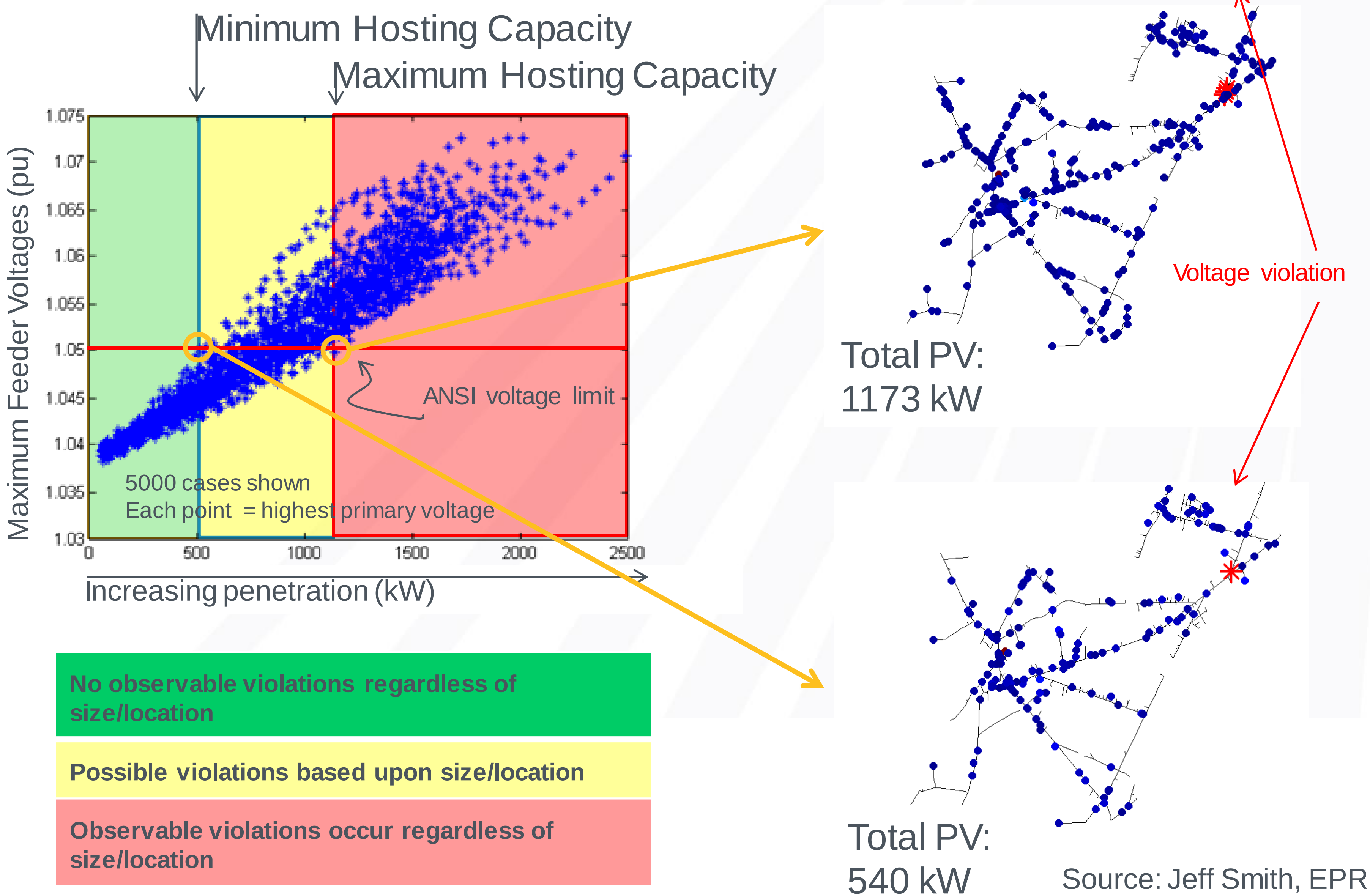


NAM 6z 0-24hr
SREF ARW-CTL 3z, 0-24hr

Forecast using "proxy site" for machine learning training shows 25% improvement in MAE

PV Hosting Capacity in Distribution Systems

(NREL, Sandia, CPUC, EPRI)



No observable violations regardless of size/location

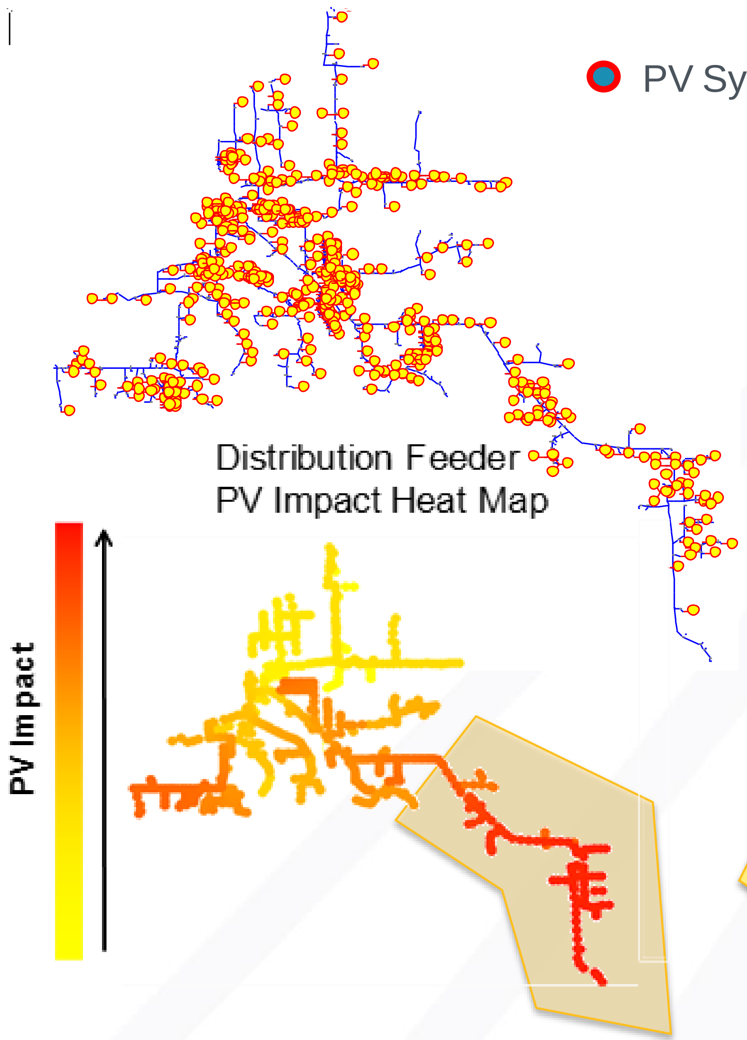
Possible violations based upon size/location

Observable violations occur regardless of size/location

Source: Jeff Smith, EPRI

PV Analysis: Determining Feeder Hosting Capacity

Leveraging an EPRI Research Project



Baseline – No PV

PV Penetration 1

PV Penetration 2

PV Penetration 3

Beyond…

Process is repeated 100's of times to capture many possible scenarios

Increase Penetration Levels Until Violations Occur

Source: Jeff Smith, EPRI

Limit of Current IEEE 1547 Standards

Table 1—Interconnection system response to abnormal voltages

Voltage range (% of base voltage[a])	Clearing time(s)[b]
V< 50	0.16
50 ≤ V< 88	2.00
110 < V < 120	1.00
V ≥ 120	0.16

[a]Base voltages are the nominal system voltages stated in ANSI C84.1-1995, Table 1.
[b]DR ≤ 30 kW, maximum clearing times; DR > 30kW, default clearing times.

Table 2—Interconnection system response to abnormal frequencies

DR size	Frequency range (Hz)	Clearing time(s)[a]
≤ 30 kW	> 60.5	0.16
	< 59.3	0.16
> 30 kW	> 60.5	0.16
	< {59.8 – 57.0} (adjustable set point)	Adjustable 0.16 to 300
	< 57.0	0.16

[a]DR ≤ 30 kW, maximum clearing times; DR > 30 kW, default clearing times.

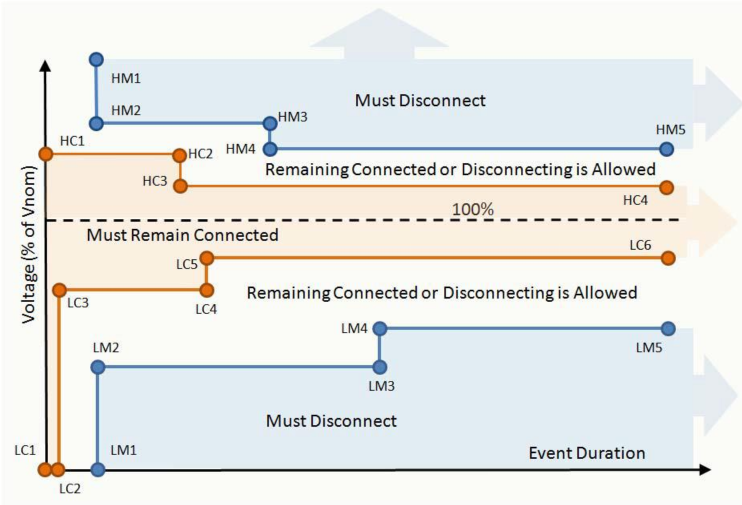
Problems:

- Large amount of PV inverters tripping off on voltage and frequency disturbances
- Causing more imbalance between generation and load
- More reserves to be called up with fast ramps

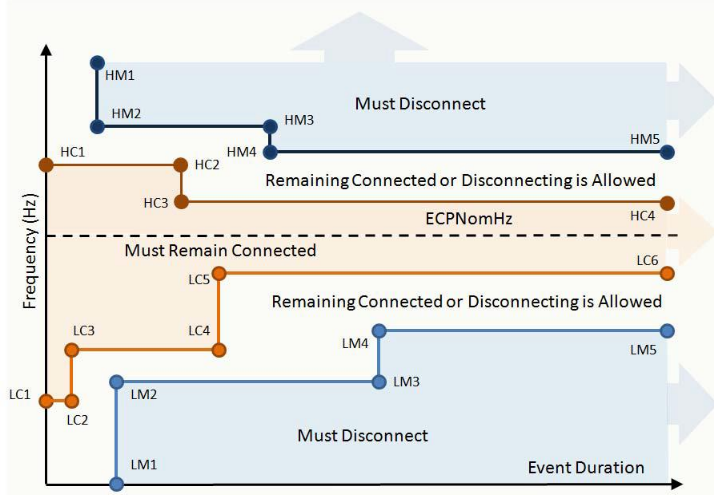
Solutions:

- Voltage Ride Through (VRT)
- Volt/Var, Volt/Watt
- Frequency Ride Through (FRT)
- Frequency/Watt
- Communication-based coordinated control

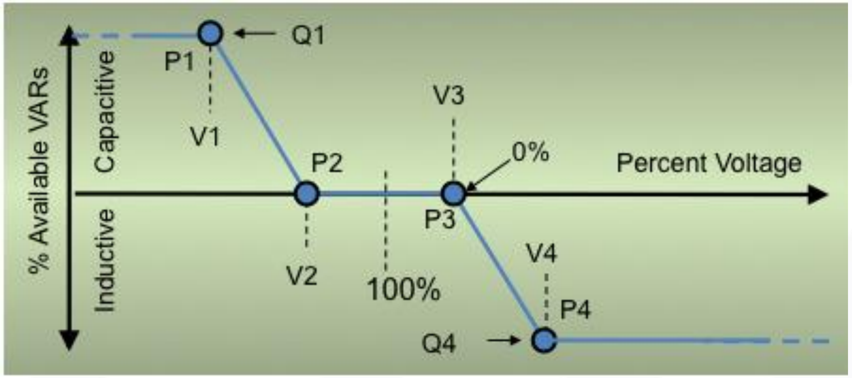
Smart Inverter Functions



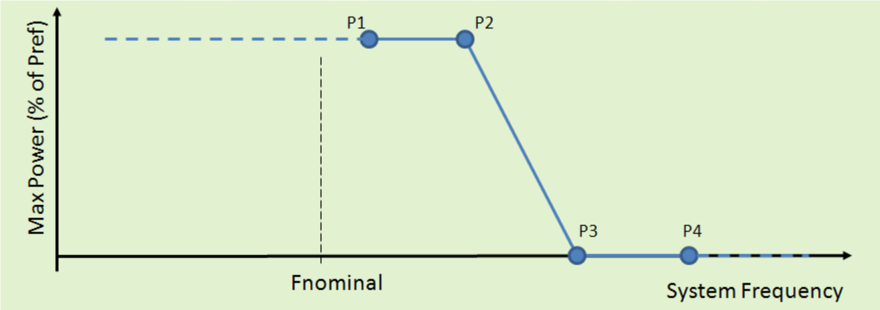
(a) Voltage Ride Through



(b) Frequency Ride Through



(c) Volt/Var



(d) Frequency/Watt

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Inverter Lab Testing

- Manufacturer lab testing
- Power HIL Modeling real feeder topology
- Using real event data

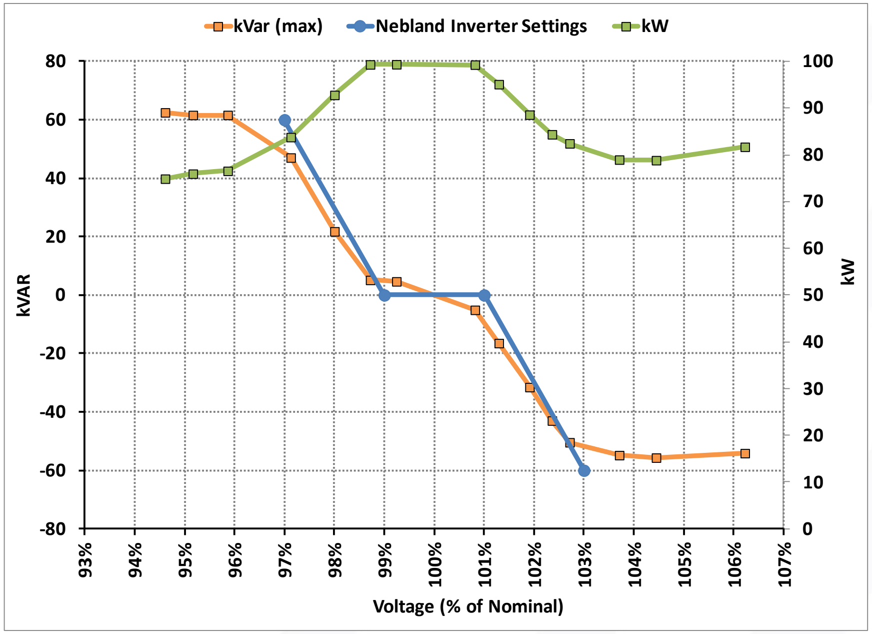
- Grid simulator
- PV simulator
- Communication
- Remote control

NREL ESIF

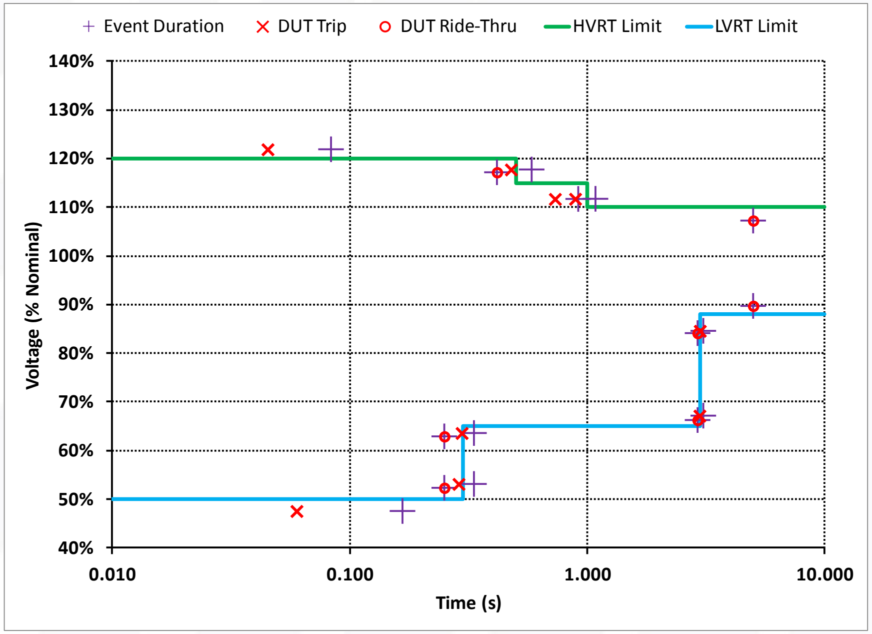
EPRI Knoxville Lab

Hardware in the Loop (HIL) Test Results

Volt/Var



L/HVRT



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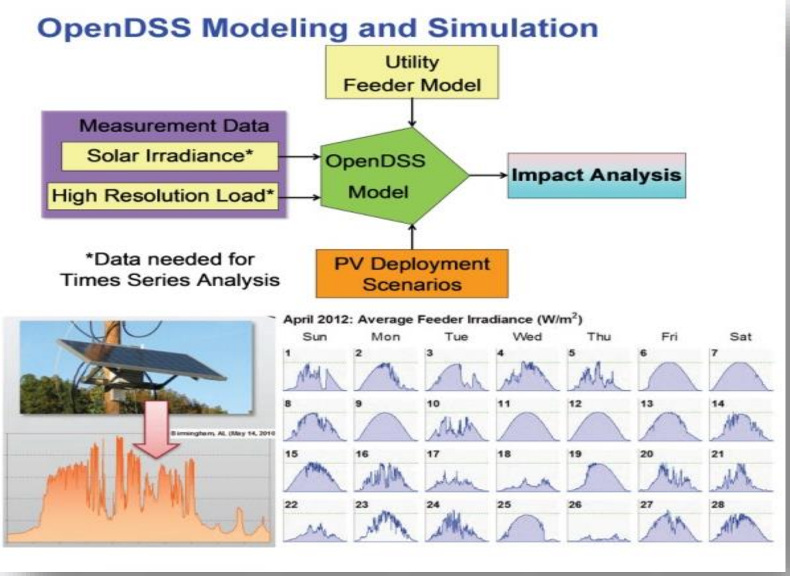
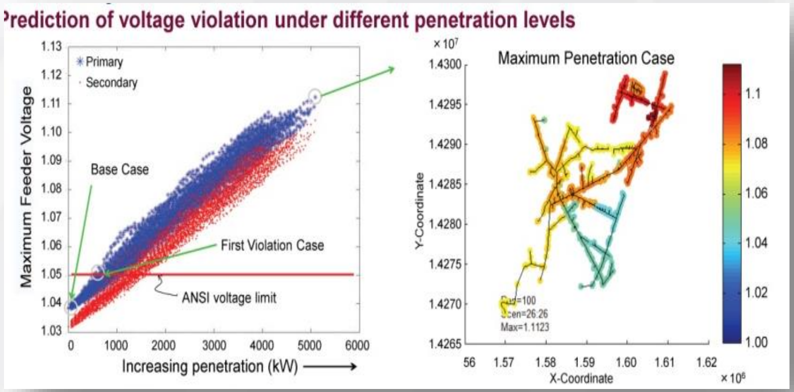
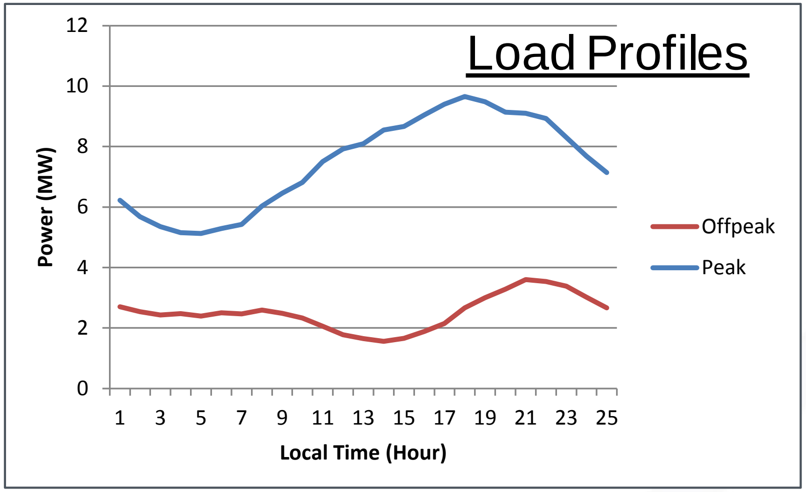
Modeling and Simulation

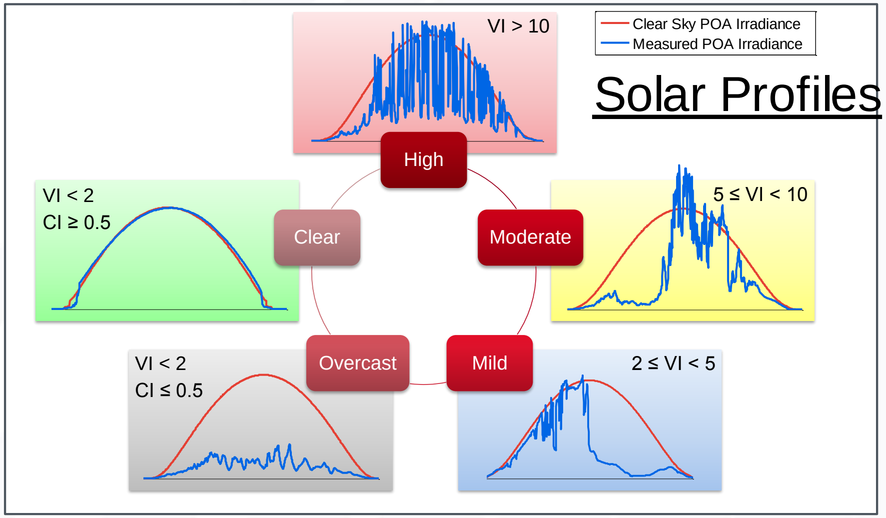
- Models
  - Solar resource model
  - Detailed feeder model
  - Load model
  - Inverter model
- Measurement data
  - Solar irradiance
  - Load
  - Grid
- Analysis
  - Quasi-time-series analysis
  - Stochastic
- Validation
  - Establish baseline
  - Quantitative metrics



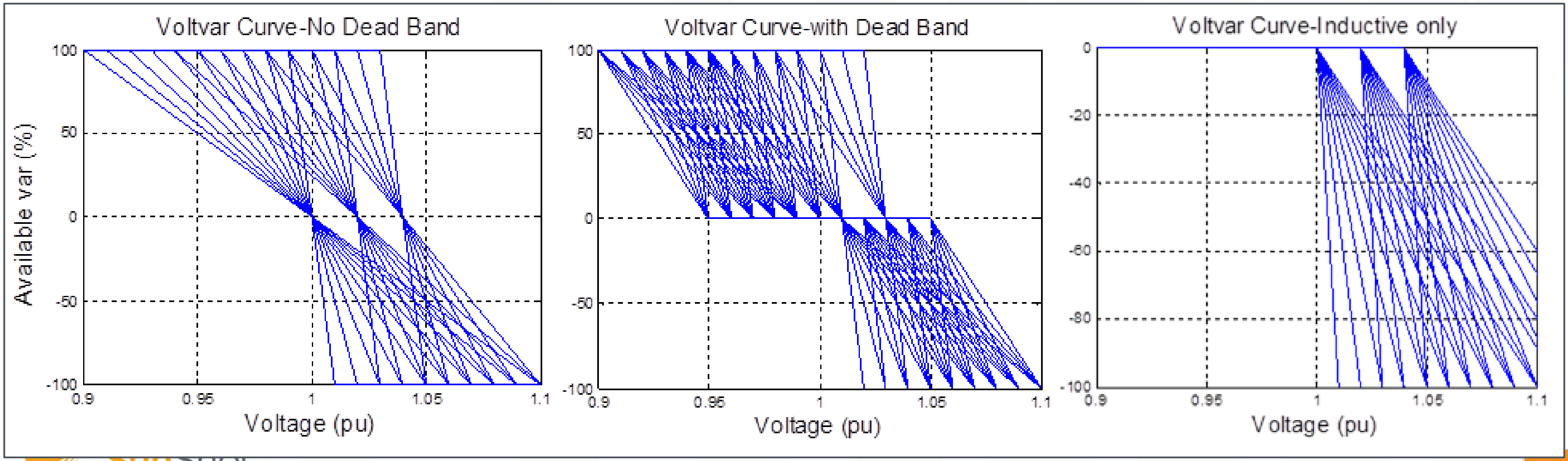


Time Series Simulation

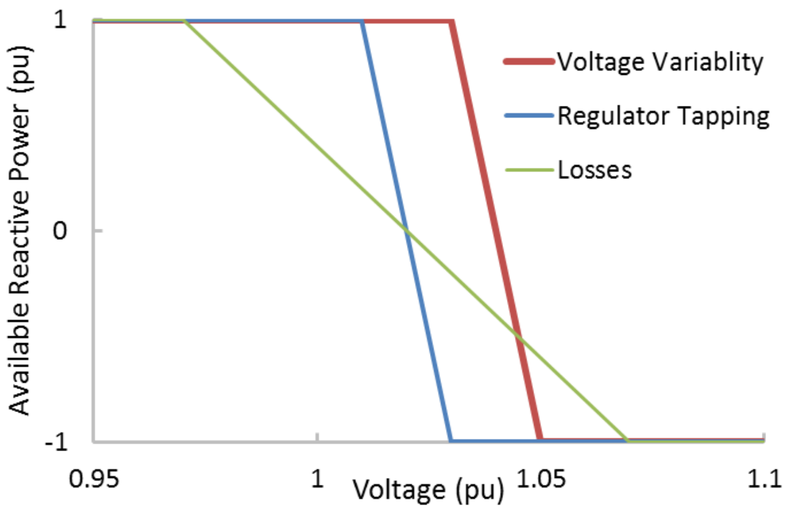




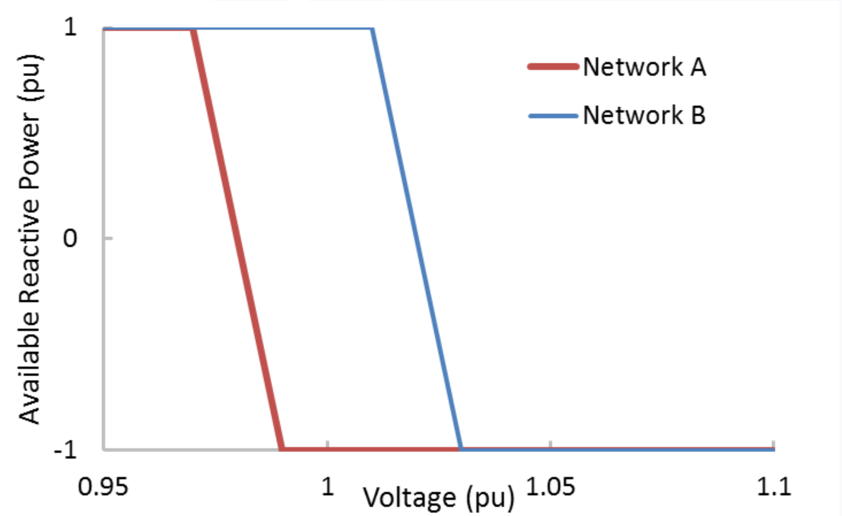
Inverter Settings



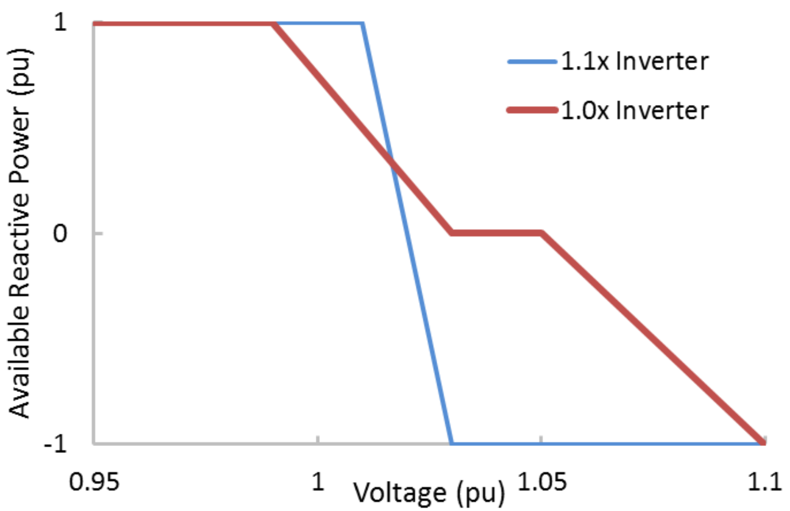
Recommended Control Settings … it depends



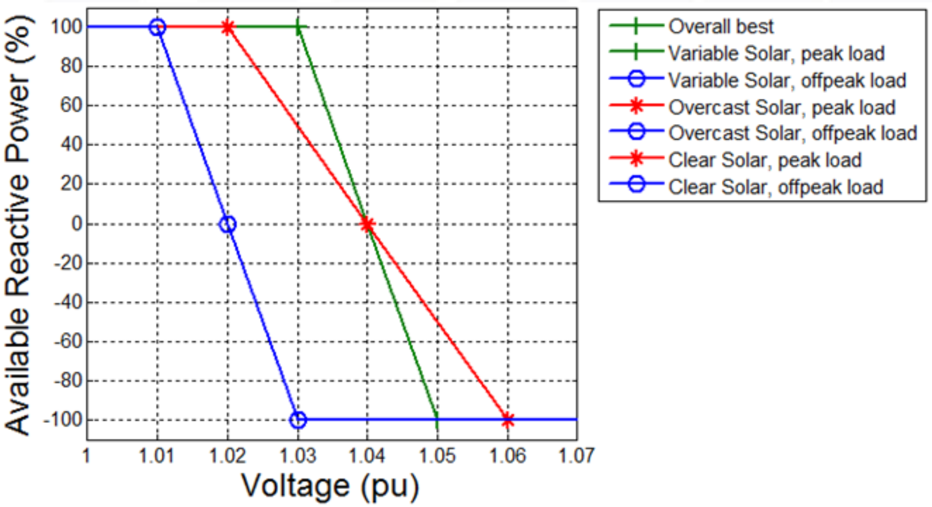
depend on performance objective



depend on feeder characteristics

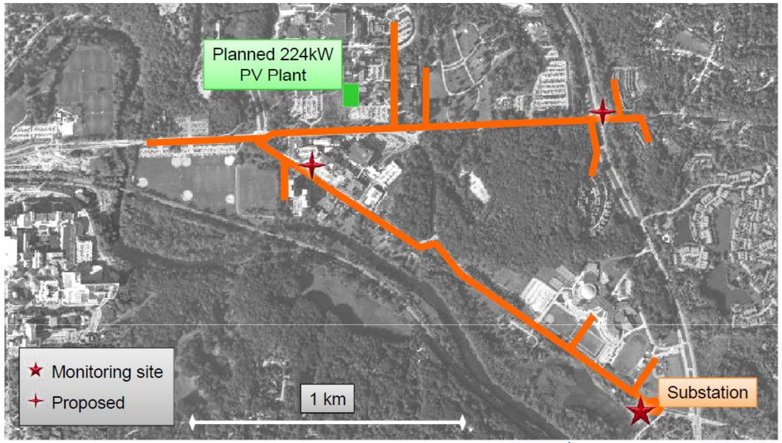


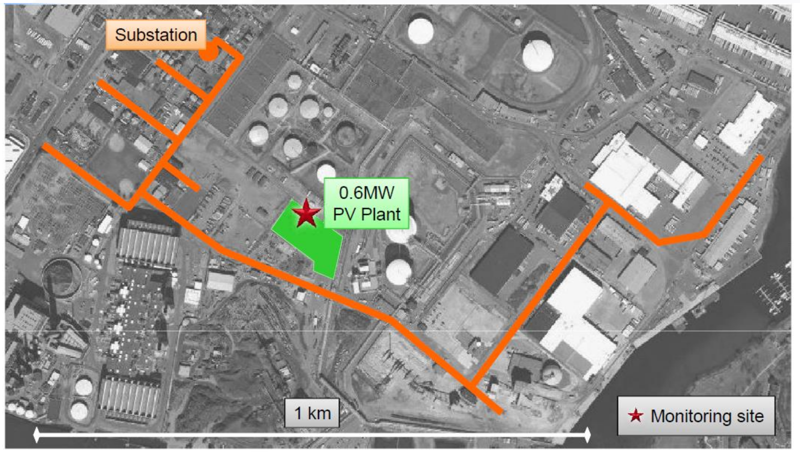
depend on inverter sizing



depend on load & solar profile

Field Demonstration with Utility Partners





- Instrumentation
- Inverter upgrade
- PMC
- Communication
- DERMS software
- Remote control

Codes and Standards Landscape

IEEE 1547 Interconnection Standards Use:

Federal, Regional, State and Local Authorities/Jurisdictions

IEEE 1547
Interconnection System and Test Requirements

- Voltage Regulation
- Grounding
- Disconnects
- Monitoring
- Islanding
- etc.

IEEE 1547.1
Interconnection System Testing

- O/U Voltage and Frequency
- Synchronization
- EMI
- Surge Withstand
- DC injection
- Harmonics
- Islanding
- Reconnection

UL 1741*
Interconnection Equipment

- 1547.1 Tests
- Construction
- Protection against risks of injury to persons
- Rating, Marking
- Specific DR Tests for various technologies

NEC

Article 690 PV Systems;

Article 705: interconnection systems (shall be suitable per intended use per UL1741)

PJM Interconnection, Inc.
Small Generator Interconnection Standards
FERC approved
(0-to<10MW and 10-to-20 MW; incorporate 1547 and 1547.1)

* UL 1741 supplements and is to be used in conjunction with 1547 and 1547.1

- California Rule 21 (Phase 1, 2, & 3)
- Coordination with NERC standards

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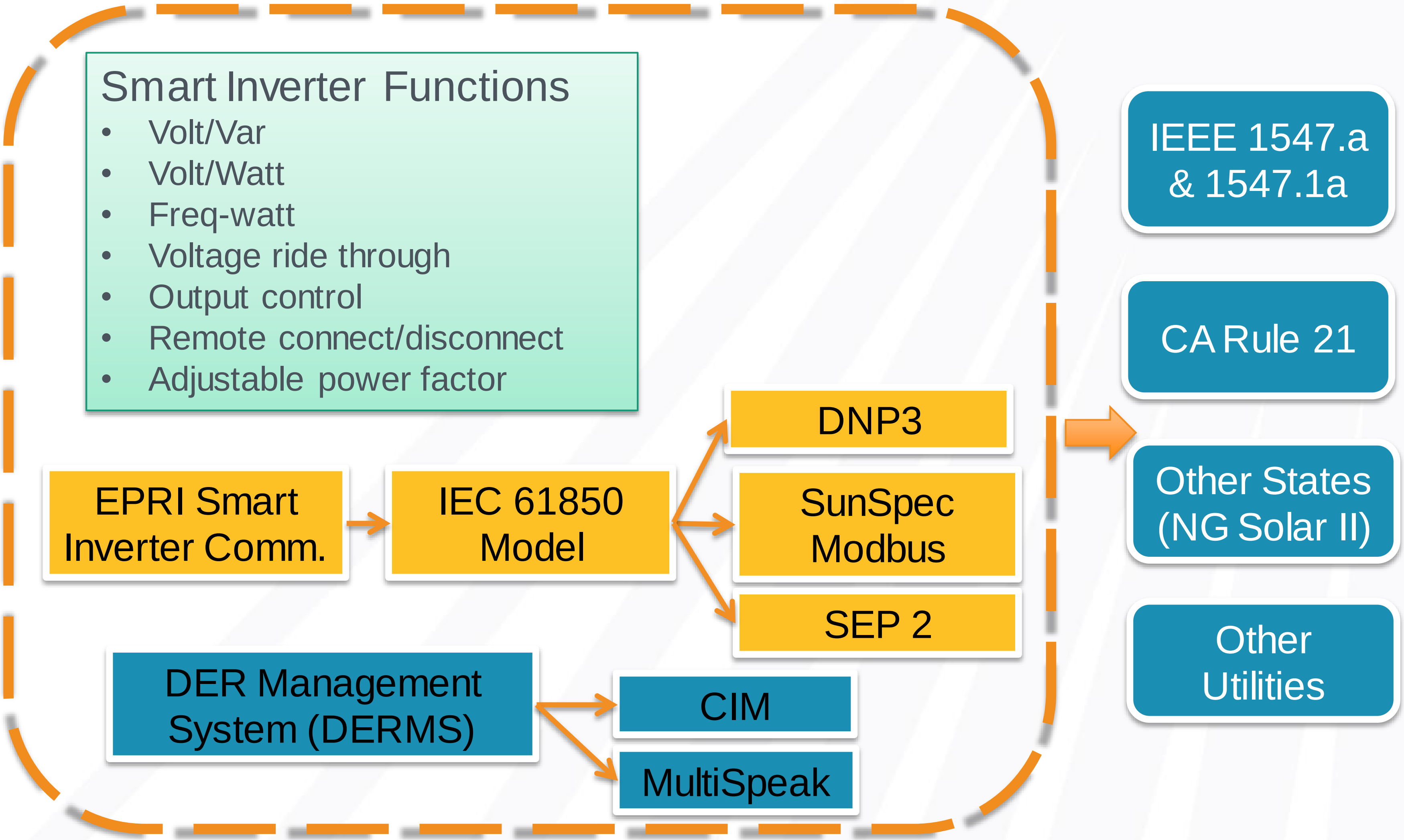
Source: Tom Basso, NREL

Lab Project #2: Accelerating Revisions of IEEE 1547 Series of Interconnection Standards for DER

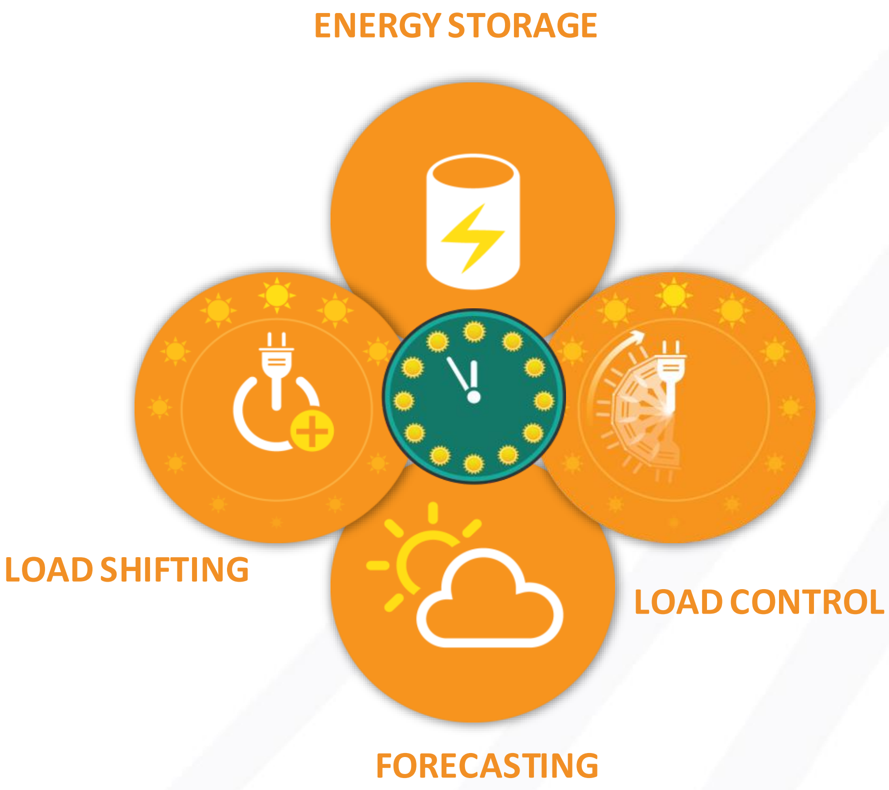
- **IEEE Std 1547™(2003 and 2014 Amendment 1) Standard for Interconnecting Distributed Resources with Electric Power Systems**
  - **IEEE Std P1547™(full revision)** Draft Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Power Systems Interfaces — Balloted in 2014
  - **IEEE Std 1547.1™(2005)** Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems
    - **IEEE Std P1547.1a™** Draft Amendment 1 — Balloted in 2014
- **IEEE Std 1547.2™(2008)** Application Guide for IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems
- **IEEE Std 1547.3™(2007)** Guide for Monitoring Information Exchange, and Control of Distributed Resources with Electric Power Systems
- **IEEE Std 1547.4™(2011)** Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems — Microgrid
- **IEEE Std 1547.6™(2011)** Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Networks
- **IEEE Std 1547.7™ (2013)** Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection
- **IEEE Std P1547.8™** Draft Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE Std 1547-2003 — Smart Inverters

Source: Tom Basso, NREL

Smart Inverter Standards



Sustainable and Holistic Integration of Energy Storage and Solar PV (SHINES)

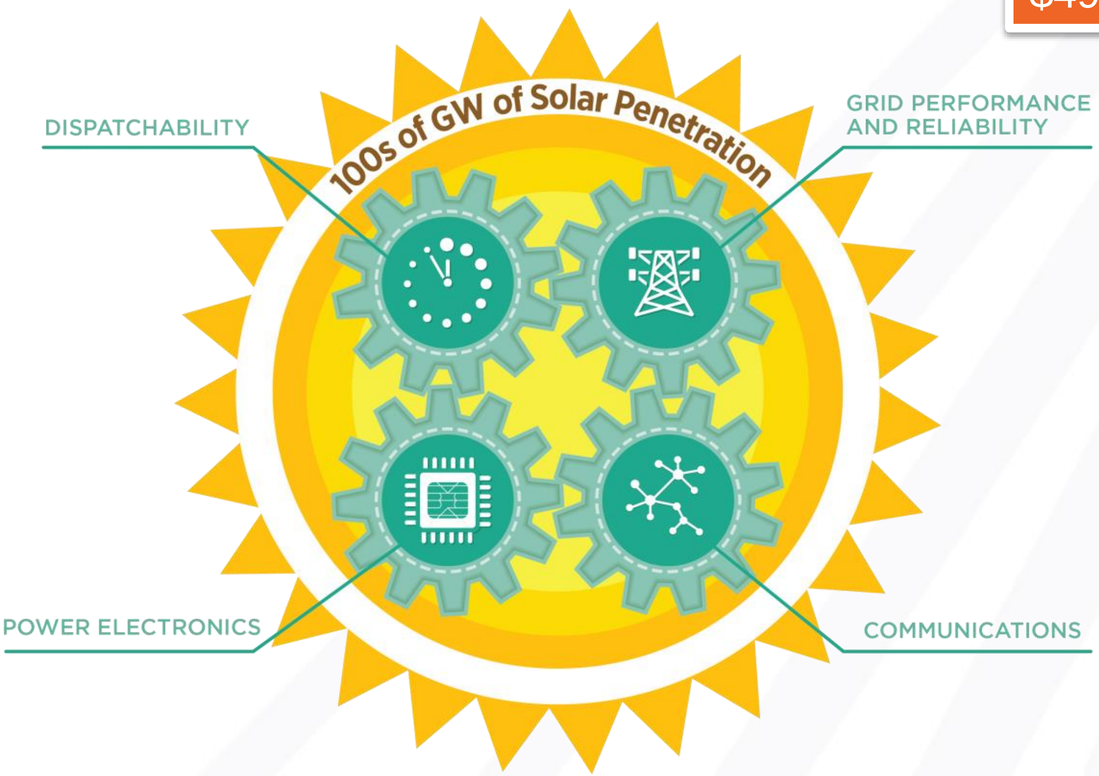


SHINES (2015)
$18M + 50% cost share

- Austin Energy
- Carnegie Mellon University
- Fraunhofer CSE
- ComEd
- EPRI
- HECO

http://energy.gov/eere/sunshot/listings/sunshot-news

SunShot National Laboratory Multiyear Partnership (SuNLaMP) – DOE Grid Modernization Initiative (GMI)



SuNLaMP (FY16-FY18)
$49M + cost share

- 8 National Labs
- 16 projects
- University and Industry partners
- Part of GMI $220M awards – cross-cutting & program-specific

http://cms.doe.gov/doe-grid-modernization-laboratory-consortium-gmlc-awards

Impact the Future of Solar Energy

Join our team! Take on the SunShot grand challenge to make solar energy cost-competitive with traditional energy sources by 2020.

Design national R&D strategies in the following areas:

- Photovoltaics
- Systems Integration
- Tech to Market
- CSP
- Soft Costs

To receive a current list of job opportunities available with the SunShot Initiative, please contact ops.solar@ee.doe.gov.

Thank You!

& Let's work together!

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